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MEMORANDUM REPORT NO. 2756

# FEASIBILITY EXPERIMENTS ON THE DEMILITARIZATION OF CHEMICAL MUNITIONS BY HIGH POWER LASERS. PART I: CUTTING EXPERIMENTS

Konrad Frank
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June 1977





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USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>MEMORANDUM REPORT NO. 2756 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>FEASIBILITY EXPERIMENTS ON THE DEMILITARIZATION OF CHEMICAL MUNITIONS BY HIGH POWER LASERS. PART I. CUTTING EXPERIMENTS. | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Konrad Frank<br>Raymond J. Roszak | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>US Army Ballistic Research Laboratory<br>Aberdeen Proving Ground, MD 21005 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>728012.211 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>US Army Materiel Development and Readiness Command<br>5001 Eisenhower Avenue<br>Alexandria, VA 22333 | | 12. REPORT DATE<br>JUN[redacted]977 |
| | | 13. NUMBER OF PAGES<br>34 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)<br>Office of the DA, Project Manager for Chemical Demilitarization and Installation Restoration<br>Aberdeen Proving Ground, Maryland 21010 | | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

| | | |
|---|---|---|
| chemical munitions | steel | chemical demilitarization |
| laser cutting | aluminum | |
| $CO_2$ laser | fiberglass | |
| gas-jet assist | cutting parameters | |
| temperature increase | specific power requirements | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (bjk)


A series of experiments was performed to demonstrate the feasibility of using gas-assisted $CO_2$ lasers for demilitarizing chemical munitions. 155mm projectiles and 115mm rocket assemblies were cut with lasers of 3.0, 6.0 and 10.5 kW delivered power. The explosives and the chemical agent were simulated by inert materials. The cutting parameters for several materials and geometries of interest and the temperature histories in critical locations are presented, and some possible trade-offs between laser power and production rates are discussed as applicable to the special case of chemical munitions.


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TABLE OF CONTENTS

## LIST OF FIGURES





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## 1. INTRODUCTION

The work reported here was performed by BRL for the Program Manager Demil. It started after Mr. Glen Shira from the PM-Demil Office contacted BRL seeking advice on this subject. We recommended that he visit suitable industrial laboratories for firsthand information on the economics of high power lasers in industrial applications. As a result of these preliminary discussions, it was decided to perform speedily a series of metal cutting experiments, using full scale, inert, ordnance materiel of interest to determine processing speed and to identify any problems peculiar to materials processing by lasers. These pilot experiments were successfully executed by BRL in November 1974 and December 1974 at the United Technology Research Laboratory (East Hartford, Connecticut), and the AVCO Everett Research Laboratory (Everett, Massachusetts), respectively, using laboratory models or prototypes of industrially rated high power $CO_2$ lasers.

These results were very encouraging. Therefore, we were asked to investigate the problems of laser radiation interacting with the explosives as found in chemical munitions. Safety requirements precluded us from using industrial facilities and we performed scaled feasibility and criticality experiments in-house, using initially a 100 watt $CO_2$ laser, and later, the BRL 4000W $CO_2$ laser, with suitable explosive containment structures as dictated by safety requirements. These experiments were concluded in December 1976 by demonstrating to the PM-Demil and his staff the successful and safe cutting of a scaled burster tube filled with live explosive.

This report presents the results of our work dealing with the potential application of lasers in the processes required to demilitarize chemical munitions, as briefly described above. Questions regarding the interaction of laser beams with the chemical agents were not addressed. Part I deals with the cutting experiments at UTRC and AVCO, and Part II describes our in-house work on confined and unconfined explosives.

## 2. MATERIALS PROCESSING BY LASERS AND POTENTIAL APPLICATIONS IN THE DEMIL PROCESS

Modern industrial processes utilize lasers increasingly for cost-effective manufacturing ranging from trimming electronic components to high speed cutting of materials, including metals, and efficient welding of metals. The power requirements range from a few watts of average power to a few kilowatts, possibly tens of kilowatts average power, depending on the process and process speed. Some processes require pulsed lasers (or repetitively pulsed lasers), others are more efficient by using continuous wave (CW) laser radiation. The most efficient lasers in industrial use today are solid state, Neodymium-doped-YAG lasers

(pulsed or CW, average powers up to 1000 W) and $CO_2$ gas lasers (up to tens of kilowatts, generally CW). At present, lasers suitable for cutting or welding thick metals are $CO_2$ lasers. Typical applications for metal processing with lasers, advantages of using lasers, and processing economics are found in References 1-6. We included only recent publications, and furthermore, only those we believe to be relevant to the problems and processes encountered in the demilitarization of chemical munitions. Reference 4 also contains a summary of laser systems produced both here and abroad and a succinct description of their salient features. According to the most recent news releases, that list is updated by noting that GTE-Sylvania is scaling up their 1.5/2.5 kW units and plans to produce 5 kW laser systems for General Motors (October 1976).

Before we discuss briefly some of the potential advantages of using lasers in the demil-process, we will attempt to catalog in a generic fashion the work required for that process. The common, generic, features of chemical munitions are:

- a metal body or container, hermetically sealed, filled with a
- toxic agent (liquid), and a
- burster charge (explosive) which upon detonation disperses the agent.
- Fuzes, rocket motors, etc. are usually removable, but in some cases may be integral to the device.

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[1] E. V. Locke and R. A. Hella, "Metal Processing with a High-Power $CO_2$ Laser," Journal of Quantum Electronics, Vol. QE-10, 1974, pp. 179-185.

[2] E. V. Locke, et al, "High Power Lasers for Metalworking," AVCO Everett Research Laboratory Inc. Research Report No. 398, March 1974.

[3] J. P. Carstens and G. L. Whitney, "Industrial Applications of High-Power Lasers," United Technologies Research Center.

[4] E. M. Breinan, et al, "Laser Welding - the Present State of the Art," United Technologies Research Center Report No. R75-111087-3, Jun 75.

[5] E. M. Breinan, et al, "Evaluation of Basic Laser Welding Capabilities," United Technologies Research Center Report No. R75-911989-4, Nov 75.

[6] C. M. Banas and G. T. Peters, "Study of the Feasibility of Laser Welding in Merchant Ship Construction," United Technologies Research Center USAL Report No. N911796-4, August 1974.

Again, in very general terms, the demil-process requires:

- the safe separation (disassembly) of the component parts,
- the disposal or the neutralization of the active ingredients (agent, explosive or propellant), and the
- decontamination of the residuals before they can be safely reintroduced into a clean environment.

These operations have to be performed in a closed, usually hermetically sealed environment (enclosure), requiring for efficient operation and high "production" rates reliable and minimum maintenance operations inside the enclosure. High power laser systems are probably capable of performing all the processes identified above. More realistically--and as demonstrated by the results reported here--the safe cutting of the "containers," either for the purpose of removing the agent or in order to facilitate further processing, and possibly the neutralization of the explosives are definite areas for Laser Applications: The high technology (complex) laser system can be located outside the sealed enclosure required for the process; the actual "working tool" is a beam of electromagnetic radiation, generated outside, and easily transported through "windows" into the enclosure and to the work piece. The hardware inside the enclosure is kept to a minimal amount, and the "tool" is precisely controllable from the outside. At this point, a few general comments about demil-processing by lasers are in order to put it into perspective vis-a-vis other, more conventional methods. The overall power efficiency of a large laser system is only about 10% ($CO_2$, fast flow gas laser, including all necessary auxillary subsystems like cooling, gas circulation, electrical power regulation, control, etc). At first this might seem low; however, nearly all the optical power generated is available as useful power on the work piece. Furthermore, it is easily concentrated (focused) on a very small area as needed for example for cutting or welding, or spread over a larger area like in the surface treatment of metals (see for example References 1-2). The processing efficiency in welding and cutting is comparable to, or better than earlier, nonlaser methodology. The "no contact" feature of laser processing is very attractive in some applications, and possibly very important in demil work. Earlier work in the applications area of interest was performed by Zwicker and Esposito (Frankford Arsenal) for the Munitions Support Directorate of Picatinny Arsenal.[7] The emphasis was on improvised explosive devices and the conclusions at that time were that lasers were impractical. The reasons given do not apply to a larger or a fixed installation processing regular explosive devices.

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[7] E. L. Roller, "The Feasibility of Using a $CO_2$ Laser in the Neutralization of Improvised Explosive Devices," Picatinny Arsenal Technical Report No. 4455, February 1973.

Another study was made by the Atlantic Research Corporation[8] for the Naval Explosive Ordnance Disposal facility. The thrust of this study was to go through the engineering design of a field-portable, 10 kW gas dynamic laser cutting tool. The effort demonstrated that there are "no major engineering or technology obstacles to building such a portable tool." Today, and especially for fixed installations, the case for using lasers in EOD or demil work is very strong indeed. There are various laser systems in daily use in production (e.g., manufacturing extended life batteries for and by Western Electric, Reference 3) and the number of applications in industry is expected to increase sharply. These industrial laser systems are reliable, efficient and cost effective in many industrial processes, and therefore may very well be equally suitable and desirable to modernize demil operations.

## 3. CUTTING EXPERIMENTS ON FULL SCALE, INERT, CHEMICAL ORDNANCE MATERIAL

The items of primary interest or concern in the chemical munitions stockpile today are projectiles (8 inch, 155mm, 105mm, 4.2 inch mortar), and rockets (115mm M55). Other munitions are of less interest or they can be easily disposed of by similar techniques. The typical, generic features of a chemical projectile are shown in Figure 1 (8 inch projectile, without supplementary charge and fuze, shown with lifting plug installed). The burster tube, filled with explosive and surrounded by the liquid agent, is difficult to remove since it also performs the function of sealing in the agent after assembly. In some munitions, e.g., the M55 rocket warhead, the seal is a permanent one made by weld. For the cutting experiments we had available to us 16 155mm HE projectile bodies, two inert M55 rockets with attached rocket motor cases in the shipping-launching tubes, and two processed M125 bomblet bodies. Burster tubes were manufactured for 8 of the HE projectiles, filled with a mixture of wax of the correct density and melting point to simulate the explosive fill, and screwed into the fuze well after filling the projectile body with the correct amount of water to simulate the chemical agent. We installed two pairs of thermocouples, as shown in Figure 2, in order to measure the temperature increase during laser cutting: one pair was located in the joint between the projectile body and the burster tube neck, the other inside the burster tube (embedded in the wax mixture adjacent to the burster tube wall) in the plane where the cut by the laser was to be made. Provisions to measure the pressure increase (if any) in the void above the liquid level were also made by installing pressure transducers. The wall thickness of the metal parts is also shown in Figure 2. The projectile body wall is 0.6 in (15.2mm), the burster tube wall was made 0.2 in (5.1mm) as appropriate for a 155mm chemical projectile.

The warheads of the two M55 rockets were prepared and instrumented in analogous fashion; no provisions were made to simulate the propellant

[8] M. Tarabochia, "EOD Laser Cutting Tool," NAVEODFAC-TR-166, Feb 74

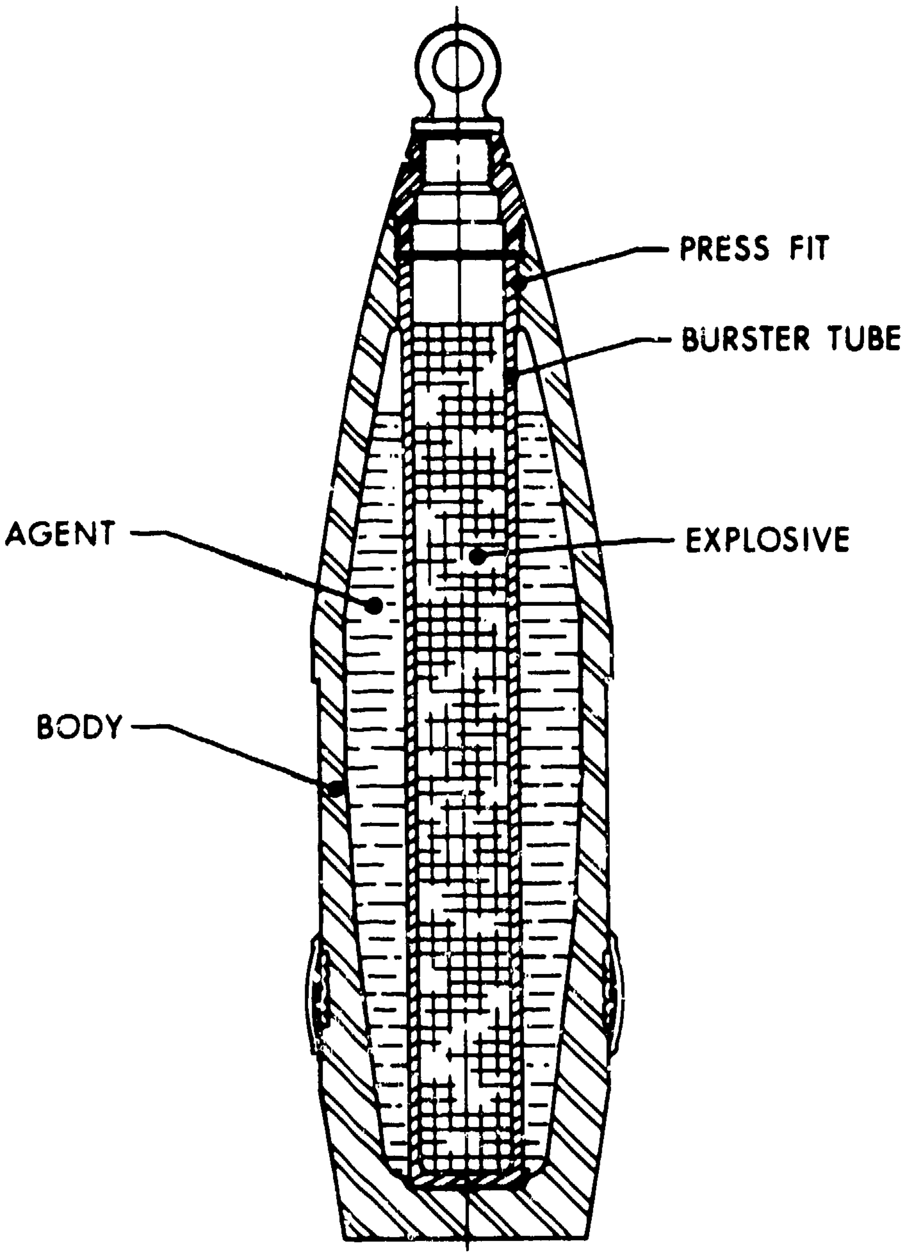


Figure 1. Typical Chemical Projectile

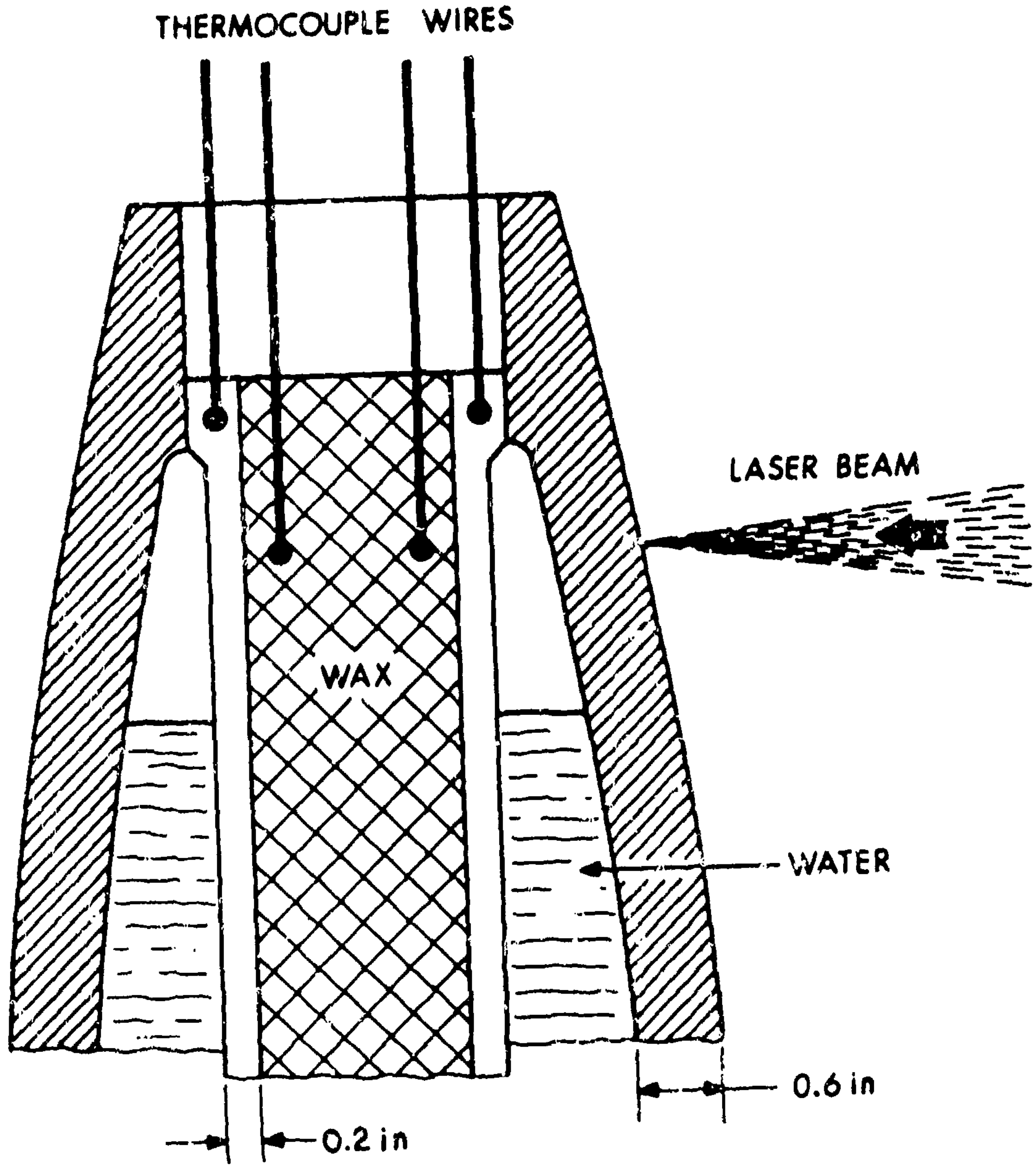


Figure 2. Instrumented 155mm Projectile

in the rocket motors and the motor cases were left empty. The somewhat mutilated M125 bomblet bodies were not prepared in any way since they were to be used primarily for fuze staking experiments. Two series of experiments were planned and carried out: The first one at the United Technologies Research Center (UTRC) in East Hartford, Connecticut, the second at the AVCO Everett Research Laboratory (AERL) in Everett, Massachusetts. We had, therefore, available to us for each series 4 each empty 155mm projectile bodies, 4 each fully simulated and instrumented 155mm chemical projectiles, 1 each fully instrumented and simulated M55 warhead with attached rocket motor case and the combination shipping and launch tube, and 1 each M125 bomblet body. It was decided to attempt complete circular cuts on all the test items. This would permit the removal of the explosive filled burster tube after the cutting operation and provide for maximum ease of draining the agent. It was considered to be a more difficult operation than just to drill or cut a single hole into the body, for example.

### 3.1 Cutting Experiments with a 3 kW and a 6 kW $CO_2$ Laser

The first test series was performed at UTRC in November 1974, using a laboratory $CO_2$ laser of up to 12 kW output power. However, the laser was operated at power levels of 3.0 and 6.0 kW in order to simulate the performance of the corresponding industrial laser types of that company. The laser produced a high quality annular beam which was focused by a very efficient f/12 optical system (Figure 3), onto the work piece. The first mirror (M1) was polished aluminum with a central hole, the actual focusing mirror (M2) was a spherical copper mirror of 37 in. (940mm) focal length; the last mirror (M3) redirecting the laser beam toward the work piece, was a flat, polished copper mirror. The test pieces were clamped on a controllable rotating table in a vertical position.

The basic difference between deep penetration welding, covered extensively in References 1-6, and CW laser cutting is the addition of a high velocity gaseous jet to remove molten material in the interaction zone. If a strongly reactive gas like oxygen is used, the cutting speed is determined significantly by the gas jet characteristics, and the cutting process is in many ways similar to the standard oxy-acetylene process. Drilling or cutting is also possible without an auxiliary gas jet, provided the laser radiation is rapidly pulsed. Each and every short pulse melts and vaporizes some material in the working zone and causes ejection of the affected material before the next pulse is applied. This mode of operation is briefly alluded to in Reference 7. At present, CW lasers are considered more efficient, but with new pulsed laser devices under development the situation may change in the future.

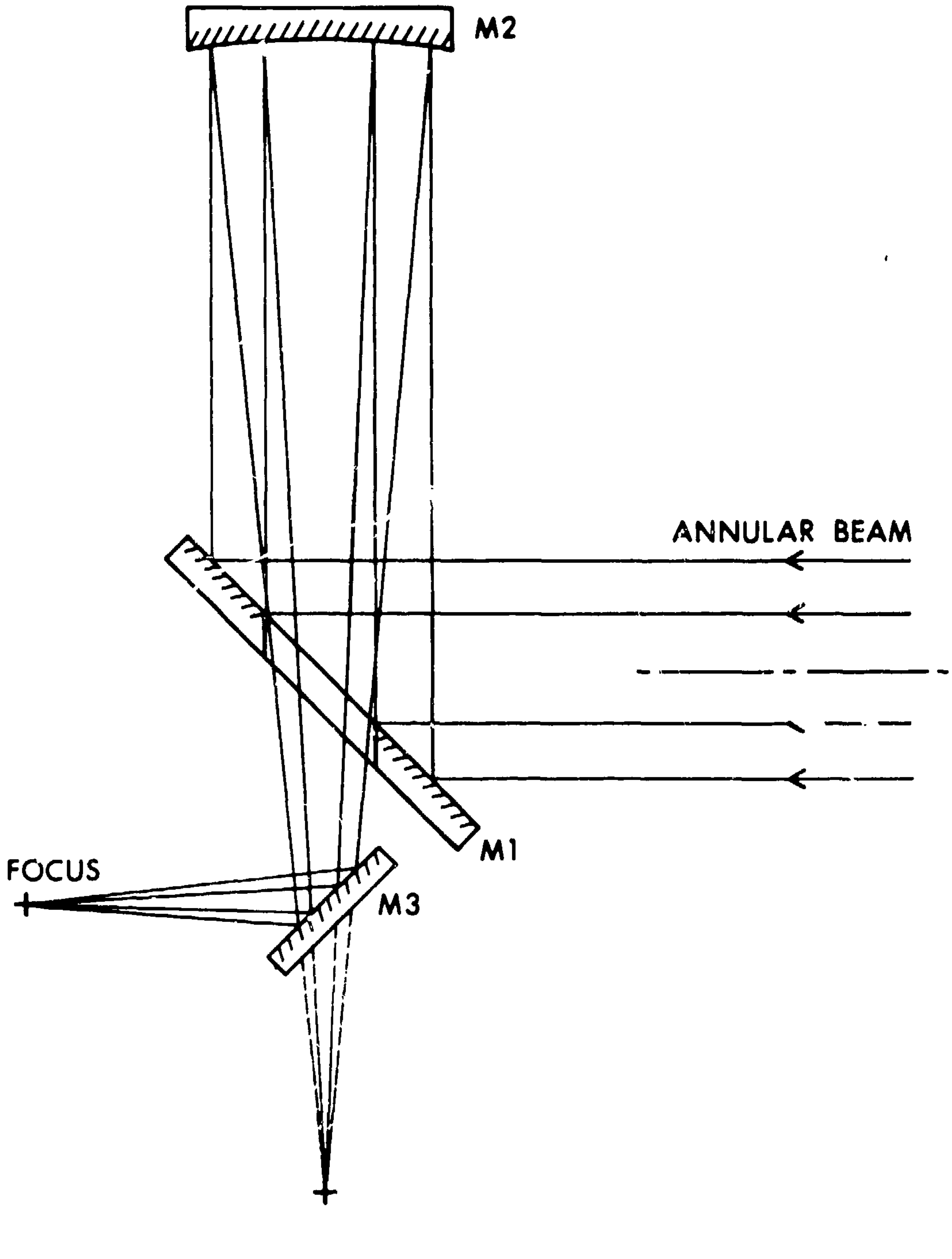


Figure 3. Focussing Optics for the 3 and 6 kW Laser

All our experiments were performed with CW laser radiation focused on the work piece and one auxiliary gas jet as shown in Figure 4. Several jet geometries and nozzle configurations (including coaxial) were tried to optimize cutting speed and insure separation after the cut was complete. The arrangement shown in Figure 4 was considered the best one: The laser beam was focused on the test specimen which was held vertically and rotated on a milling machine head. The jet was directed into the focal region from a stationary nozzle, <u>against</u> the direction of rotation. We found by experimenting that clean and complete cutting was possible if the residual spray of sparks and molten particles was directed about equally in both directions from the work area, as indicated in Figure 4.

### 3.1.1 <u>Cutting Experiments on 155mm Projectiles</u>

The optimum cutting parameters, like depth of focus, direction of the gas jet, speed of rotation, jet volume and velocity, were determined for the two power levels of interest (3 kW, 6 kW) by performing many practice cuts on the 4 uninstrumented projectiles. The operations were visually observed through black lucite panels surrounding the work area, and also directly photographed by a 16mm camera operated between 50 and 200 frames per second for closer analysis. After suitable parameters were established, the instrumented projectiles were cut at the two power levels and the temperature and pressure data were recorded together with timing information of applied laser power on a calibrated 6-channel recording system. Exactly timed movie records were also obtained. Note that in Figure 4 the laser beam is not penetrating through the body wall into the void, and ideally it never reaches the burster tube. This ideal situation could be closely obtained in practice. On the inside of the projectile body, slag and resolidified melt sometimes forms a bead which prevents the separation of the completely cut pieces. This was not considered to be a serious problem. A second, additional jet could keep the fresh cut open and inhibit the formation of a melt/slag bead on the inside and across the cut. Another problem occurs if the laser beam is not shut off immediately after completing one revolution of the work piece. The laser beam then penetrates through the cut in the body and propagates to the burster tube. The thickness of the burster tube is only 1/3 that of the body. The beam on the burster tube is slightly defocused, and there is no efficient jet for melt removal on that location. Nevertheless, the thinner burster tube wall is sometimes easily penetrated by the laser beam, so that both projectile and burster bodies may be cut, as was indeed the case in some experiments. This problem is easily solved by offsetting the laser beam axis from the projectile axis sufficiently so that no penetration of the burster tube can occur, but this reduces the cutting speed.

The following cutting speeds were determined in the final, successful experiments using fully simulated 155mm chemical projectiles as described earlier:

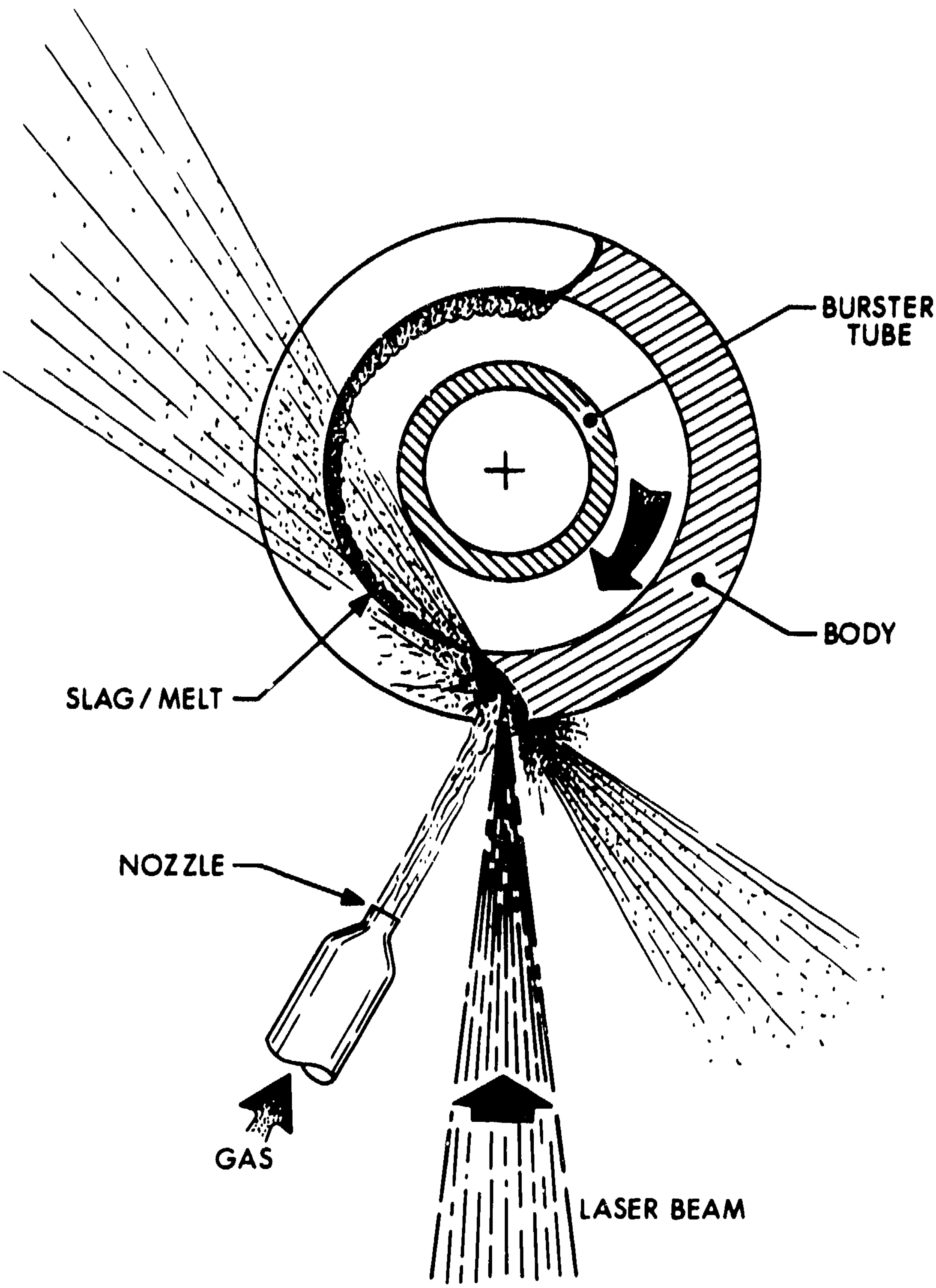


Figure 4. Cutting Geometry

| Laser Power | Cutting Speed |
|---|---|
| 3 kW | 35 in/min (1.48 cm/sec) |
| 6 kW | 50 in/min (2.12 cm/sec) |

The speed is referenced to the outside diameter of the body. In both cases an oxygen jet was used. The nozzle was a 0.060 in. (1.5mm) diameter stainless steel tube connected with 1/8 in. copper tubing to a 330 psi (2.27 MPa) gas reservoir. The pressure increase in the void above the agent (see Figure 2) was not significant. We recorded a maximum increase of 1/3 atmosphere (5 psi) which dropped to atmospheric as soon as a complete cut started to form (less than 1 sec). The temperature rise was surprisingly low. The highest temperature increases were experienced with 6 kW of laser power, as expected. Listed below are the recorded temperatures on a successful 6 kW cutting experiment.

| Time (sec) | TC1 (deg. C) | TC2 (deg. C) |
|---|---|---|
| 0 | 25 | 25 |
| 20 | 32 | 25 |
| 40 | 74 | 25 |
| 150 | 150 | 75 |
| 200 | 150 | 82 |

The time is measured from the start of the cutting operation which for this particular case was completed in less than 14 seconds. TC1 is the average of the two thermocouples in the burster tube neck, and TC2 the average of the two thermocouples embedded in the wax, inside the burster tube, and in the cutting plane (Figure 2). During the cutting operation, lasting from 0 to 14 seconds, no measurable temperature increase was recorded at either station. After 18 seconds, Station 1 (located in the neck of the burster tube) registered a measurable increase. From then on, the temperature increased steadily until about 150 sec, where the maximum for TC1 was reached. The temperature at TC2 was always lower than at TC1, indicating that the transport of heat occurred mainly through the projectile body, into the burster tube neck joint, and down into the wax simulating the explosive (see Figure 2). No significant heat transfer took place between the cut in the body, and the burster tube directly across from it. In any case, the significant temperature rise occurred after the cut was completed and it could be easily arrested by subsequent cooling if so desired. Additional temperature measurements were made by applying strips of "tempilaq" of various transition temperatures on the outside of the projectile. These were recorded on film during the cutting operation, and they confirmed after careful evaluation of the movie records, that the main source of heat is generated only in the cutting plane of the projectile body. This heat then travels through the projectile body, into the burster tube and transfers finally to the simulated explosive. During the actual cutting operation, the heat transferred to the simulated explosive

was insignificant. The total heat input for cutting at 3 kW laser power was considerably less, and much smaller temperature increases were recorded. In addition, we performed a metallographic analysis of an incomplete cut to determine the 720°C phase transition boundary and the width of a 3 kW cut. We found a cut (kerf) width of 0.05 in. (1.35mm) and the 720°C boundary 0.175 in. (4.5mm) away from the cutting plane.

The phase transition boundary separates the material which exceeded the transition temperature of 720°C from that which always stayed below that temperature. From the data above, the temperature gradient for this particular case is determined approximately as (1520-720)/4.5 = 178°C/mm near the cutting plane (3 kW power, 1.48 cm/s cutting speed). In the 6 kW experiments we observed somewhat larger gradients.

These experiments proved the feasibility of cutting 155mm chemical projectiles. Since the largest projectile of interest, an 8 inch, is only a 4/3 larger scale of the 155mm, no fundamental problems or difficulties are expected in the cutting of chemical projectiles by high power $CO_2$ lasers. The larger wall thickness-0.8 in. (20mm) versus the 0.6 in. (15mm) used in these experiments-- is easily compensated for by increasing the laser power or decreasing the cutting speed. The smaller projectiles in the inventory should present no problems.

### 3.1.2 Cutting Experiments on M55 Rockets

The M55 chemical rocket is very different from chemical artillery projectiles: The warhead is constructed from thin-walled aluminum alloy and filled with agent after the burster well is installed and welded to the projectile body. The characteristic features of the complete assembly are shown in Figure 5: The warhead is screwed into the steel case of the rocket motor and the complete flight package is contained inside a fiber glass tube serving both as the shipping container and launch tube. The rocket was simulated and instrumented similar to the 155mm projectiles: The burster tube well was filled with wax to simulate the explosive, thermocouples were installed in locations corresponding to Figure 2, and the warhead was filled with the correct amount of water to simulate the agent. The rocket propellant was not simulated for these tests and the rocket motor case was left empty. It was decided to make all necessary cuts without removing the rocket from the shipping-launching tube.

Since only one specimen was available for the test, a large number of practice cuts were made using similar materials and similar geometries. For the final cuts, we performed a "top" cut and a "base" cut as shown in Figure 5. For the base cut we attached additional thermocouples to the aluminum body adjacent to the end of the motor case. In all the tests no measurable temperature increases were recorded. This is attributed to the good thermal conductivity of aluminum (4.5 x

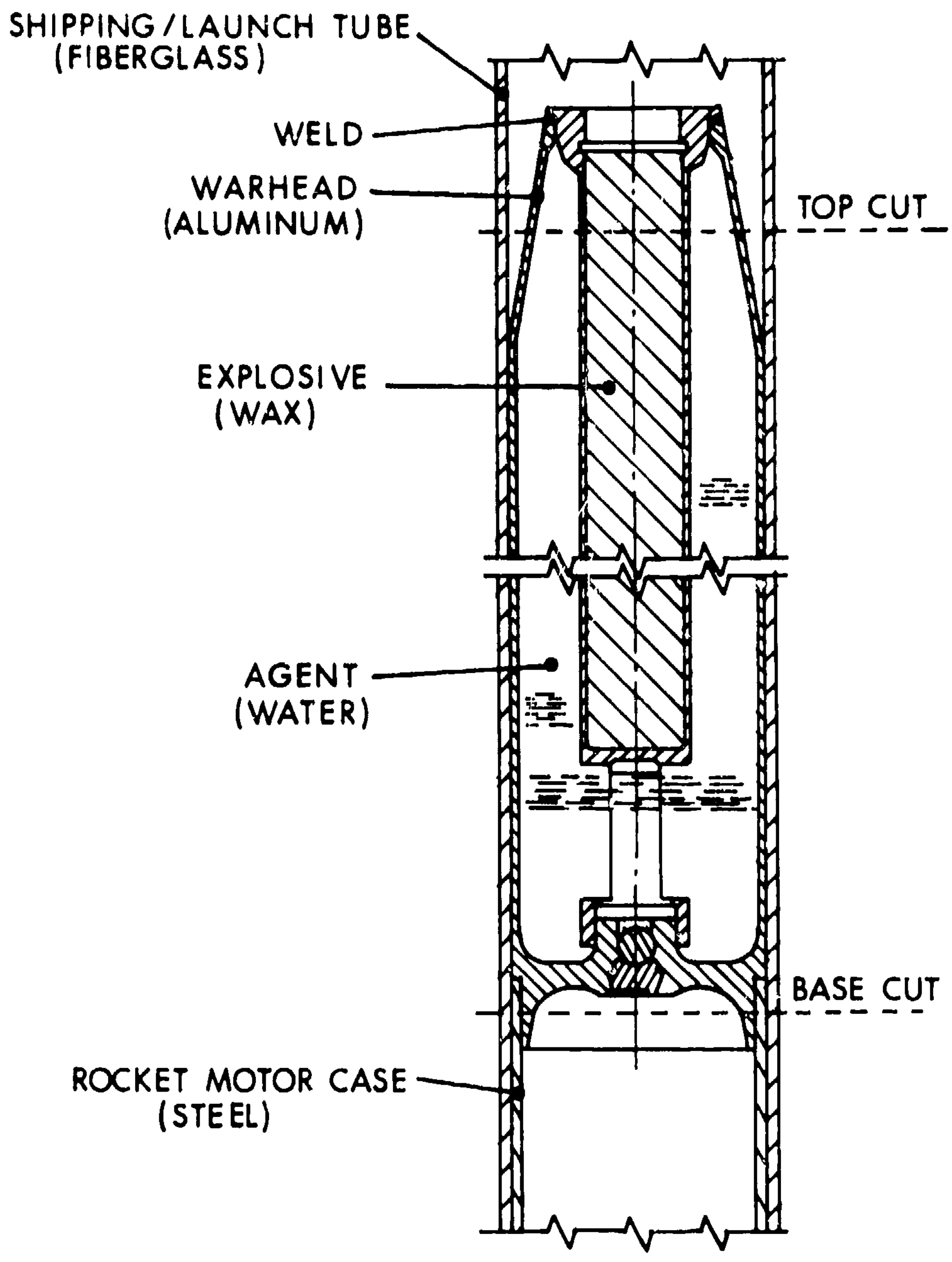


Figure 5. M55 Rocket Assembly

greater than iron, 14.6 x greater than stainless steel), the thin wall construction of the warhead, and the large body of water (agent) inside the warhead which served as a very efficient heat sink. The two cuts indicated in Figure 5 were successful. There were some initial difficulties because the wall thickness on the actual specimen did not conform to that on the drawing (top cut). In the table below, we list the cutting parameters which were determined on the actual sample rocket. The thicknesses t1, t2 and t3 are those of the shipping tube, the (steel) motor case and the (aluminum) warhead, respectively, which were simultaneously cut.

| t1<br>in (mm) | t2<br>in (mm) | t3<br>in (mm) | Power<br>kW | Gas<br>- | Cutting Speed<br>in/min (cm/s) |
|---|---|---|---|---|---|
| 0.2 (5.1) | - | - | 3.0 | $CO_2$ | > 80 (3.4) |
| - | - | 0.37 (9.4) | 3.0 | $CO_2$ | 20 (0.84) |
| 0.2 (5.1) | 0.1 (2.5) | 0.30 (7.6) | 3.0 | $O_2$ | 60 (2.54) |
| 0.2 (5.1) | 0.1 (2.5) | 0.35 (8.9) | 6.0 | $CO_2$ | 15 (0.64) |
| 0.2 (5.1) | 0.1 (2.5) | 0.42 (10.7) | 6.0 | $CO_2$ | 10 (0.42) |
| 0.2 (5.1) | 0.1 (2.5) | - | 6.0 | $CO_2$ | 30 (1.27) |
| 0.2 (5.1) | 0.1 (2.5) | - | 3.0 | $O_2$ | 60 (2.54) |

The cutting speeds are referred to the outside diameter of the work piece. For example, the base cut--4.9 in. (125mm) outside diameter-- was completed in less than 16 seconds, for the case of 3 kW laser power, oxygen jet, and 60 in/min (2.54 cm/s) cutting speed. The top cut was made in two steps. First, the shipping tube was removed by cutting 5mm below the desired cutting plane, with the warhead in place. This operation had no observable or measurable (temperature) effect on the warhead proper. The cut end of the shipping tube was then removed, the laser refocused on the warhead, and the projectile body was cut in the second step of the operation. The cut was very clean, with no other marks on the burster tube behind the cut except some fine aluminum spray deposited there by the jet. In retrospect, it would have been much easier to perform the cutting operation necessary to remove the burster tube from the agent by turning the warhead assembly upside down, and cutting the warhead and the shipping tube simultaneously just above the base of the warhead (see Figure 5). There is no explosive in that plane, and no special precautions would be necessary to insure that the explosive is not penetrated by the laser beam.

### 3.1.3 Experiments on M125 Bombs

There was not sufficient time to perform any expriments on the M125 bomblet bodies at the UTRC facilities. The problems were discussed in some detail, however. No special difficulties were anticipated on these particular items.

## 3.2 Cutting Experiments with a 15 kW $CO_2$ Laser

The second set of experiments was performed in December 1974 on the industrial prototype laser (HPL-10) at AVCO's Everett Research Laboratory. This laser system is described in detail elsewhere[1,9]. Our experiments were performed on Work Station 1, with f/7 Cassegranian optics. Approximately 70% of the available laser power reached the work piece. The laser itself is capable of more than 20 kW output, the industrial rating is 15 kW (10.5 kW delivered to the work piece at Work Station 1). The general setup and operation was similar to that used at UTRC (Section 3.1). The higher laser power prompted us to use primarily air jets for the cutting of steel, and in some cases, the higher power posed special problems, as discussed below.

### 3.2.1 Cutting Experiments on 155mm Projectiles

The general setup of the experiments is shown in Figure 4. In principle, it was identical to that used at UTRC. Some experiments were also made with coaxial jets (nozzles) but the results with side jet (Figure 4) were generally better. We also experimented with an offset geometry. The laser beam was offset from the projectile axis to assure that the burster tube was not cut when the projectile body was penetrated.

With an air jet, complete penetration was obtained at 60 in/min (2.54 cm/s). The cut, however, could not be separated. A resolidified bead formed on the inside (Figure 4) which prevented separation. In order to obtain reasonably easily separable parts the speed had to be reduced to 30 in/min (1.27 cm/s). During the experiments we observed occasionally plasmatrons (air or gas breakdown in the high intensity focal region, forming a luminous bubble of high intensity which absorbs a substantial portion of the laser energy and prevents it from reaching the work piece). The phenomena are known to occur in stationary gases

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[9] E. Hoage, et al, "Performance Characteristics of a 10 kW Industrial $CO_2$ Laser System," AERL Research Report No. 396, Feb 74 and Applied Optics, Vol. 13, Aug 74, pp. 1959-1964.

and they are enhanced by the presence of target materials.[10] Usually their formation is prevented by an airflow of moderate velocity across the focal region and the target. The plasmatrons observed here formed close to the target surface, increased in size and dissipated rapidly. An examination of our high speed film records showed that at 10.5 kW power delivered to the work piece plasmatrons formed about every 1-2 seconds and lasted for less than 20 milliseconds. We suspected that the relatively poor cutting performance may be in part attributed to these phenomena. In one experiment, we varied the laser power from 7.0 kW to 10.5 kW, keeping the cutting speed constant at 30 in/min (1.27 cm/s). Plasmatrons were observed at powers above 9.0 kW. Below 10 kW, however, the projectile body was not completely penetrated and cut. Apparently, occasional short duration plasmatrons as observed in these tests have no significant effect on cutting performance.

With an oxygen jet higher cutting speeds were obtained. Complete penetration was observed with 10.5 kW at about 100 in/min (4.2 cm/s) but a resolidified bead formed which made it impossible to separate the parts. Good separation was obtained after reducing the speed to 75 in/min (3.2 cm/s) with no offset, and to 70 in/min (3.0 cm/s) when an offset of 1 inch (2.54 cm) was used.

Below we list the cutting parameters as determined on the 155mm projectiles with a wall thickness of 0.6 in (15.2mm). All were obtained for 10.5 kW of power focused on the work piece, corresponding to 15 kW of laser power. The higher numbers are for complete penetration, but no separation after cutting. They are included here because we believe separation could be assured with an additional jet to keep the completed cut open.

| Power kW | Offset in(mm) | Gas - | Cutting Speed in/min (cm/s) |
|---|---|---|---|
| 10.5 | 0 | Air | 60 (2.50) |
| 10.5 | 0 | Air | 40 (1.70) |
| 10.5 | 1.0 (25) | Air | 30 (1.30) |
| 10.5 | 0 | $O_2$ | 100 (4.20) |
| 10.5 | 0 | $O_2$ | 75 (3.20) |
| 10.5 | 1.0 (25) | $O_2$ | 70 (3.30) |

The fully instrumented-simulated tests were made both with oxygen and air, and with and without offsetting the laser beam. The tempera-

[10] F. J. Allen, et al, "On the Ignition and the Ensuing Behavior of Laser Supported Combustion Waves," Ballistic Research Laboratory Report No. 1965, February 1977. (AD #B017343L)

ture records showed that in any case a signficant amount of heat was transferred directly to the burster tube. On successful experiments measurable temperature increases were recorded in the wax (Figure 2) very early, in the first half of the cutting operation. The melting point of the wax was normally reached before the completion of the cutting operation, and the temperature remained from then on at that level. The thermocouples in the neck of the burster tube (Figure 2) usually registered measurable temperatures in the second half of the cutting operation and from then on increased steadily up to a maximum of 150°C, which was reached about 70 seconds after the completion of the cut.

The initial pressure increase in the void above the water level (Figure 2) was similar to that in the UTRC experiments (about 5 psi) and the pressure dropped back to nearly atmospheric as soon as the cut was completely through. However, during the cutting we usually observed steam and vapors escaping through the open cut. The loss of liquid during the cutting was determined by refilling the projectile after the cutting operation to the original fill level. The losses ranged from practically none to as much as 150 milliliters on the cuts which were considered successful.

### 3.2.2 Cutting Experiments on M55 Rockets

After practicing on mock-ups, the following cutting data were established in the final experiment (see Section 3.1.2).

| t1 in (mm) | t2 in (mm) | t3 in (mm) | Power kW | Gas - | Cutting Speed in/min (cm/s) |
|---|---|---|---|---|---|
| 0.2 (5.1) | - | - | 10.5 | Air | 400 (17) |
| 0.2 (5.1) | 0.1 (2.5) | 0.38 (9.7) | 10.5 | Helium | 60 (2.5) |
| - | - | 0.25 (6.3) | 10.5 | Air | 200 (8.5) |
| - | - | 0.37 (9.4) | 10.5 | Air | 100 (4.3) |

The top cut on this experiment was a failure. We expected a wall thickness of 0.37 in (9.4mm), as found on the other specimen in the UTRC Test series. From mock-ups, we determined the correct speed as about 100 in/min (4.2 cm/s) and this setting was used for the one and only instrumented test for the top cut (Figure 5, Section 3.1.2). The actual wall thickness on this specimen was but 0.25 in (6.3mm), as was found after the test. The cutting speed for this thickness should have been two times greater, as determined later on the same sample and listed above. With the slower speed the outer body and the burster tube were cut simultaneously with spectacular results, and no meaningful temperature data could be obtained.

The remains of the burster tube were installed, approximately centered, for the cut at the faster speed (200 in/min, 8.5 cm/s). The exposed wax was ignited by scattered laser radiation, and the burster tube was partially penetrated. These results suggest that most likely much lower laser powers must be used for this particular cut, with correspondingly decreased cutting speeds.

### 3.2.3 Experiments on M125 Bombs

The M125 bomblet is a steel canister of about 3.6 in (91.5mm) outside diameter with a central burster tube of 1.65 in (42mm) diameter. The walls are 0.060 in (1.52mm) thick except near the fuze end, where the thickness increases to 0.30 in (7.6mm). The samples on hand were processed through a Demilitarization Plant, painted, and had a dummy fuze and a safe-arm wire loop. In addition to the cutting tests, we performed the following:

a. Spot welding the safety wire:

This was successfully done, without any prior removal of the body paint, by using 2 kW over an area of 0.1 in. (2.5mm) diameter, for 0.6 to 1.0 sec.

b. Fuze Staking:

This involved the joining of two dissimilar materials (anodized aluminum and painted steel) to prevent arming of the fuze. It was succesfully accomplished by the application of 10.5 kW for 1 second, again over a 0.1 in. (2.5mm) diameter area.

The cutting of the steel parts presented no problems. With an air jet and 10.5 kW power, the 0.06 in. (1.5mm) thickness was cut between 200 and 300 in/min (8.5 - 13 cm/sec) and the 0.3 in (7.6mm) thickness at 100 in/min (4.2 cm/s). The parts separated easily.

## 4. SUMMARY AND DISCUSSION OF RESULTS

The results of the cutting experiments are summarized in Tables 1-3, separated according to materials. In Table 1 we list all the results obtained on steel parts. As noted earlier, good penetration was usually obtained at higher cutting speeds, but resolidification of molten and only partially removed material sometimes caused difficulties, the cut parts were not separable. This occurred only with the 155mm projectiles, where the wall thickness was 15.2mm. In the tables, we also list the total time required to complete a circular cut, and the total laser energy used for a complete cut (the numbers in the tables are rounded off consistent with the accuracies of measuring the relevant parameters). We included some numbers, shown in parentheses, for the 10.5 kW results

TABLE 1. Cutting of Steel Cylinders by Gas-Assisted $CO_2$ Laser

| t mm | d mm | t/d - | P kW | Gas - | Speed cm/s | T sec | W kWs |
|---|---|---|---|---|---|---|---|
| 15.2 | 90 | 0.17 | 3.0 | $O_2$ | >1.5 | >19.1 | <57 |
| 15.2 | 90 | 0.17 | 6.0 | $O_2$ | >2.1 | <13.3 | <80 |
| 15.2 | 90 | 0.17 | 10.5 | $O_2$ | 3.2 | 8.8 | 92 |
| 15.2 | 90 | 0.17 | 10.5 | $O_2$ | (4.2) | (6.7) | (70) |
| 15.2 | 90 | 0.17 | 10.5 | Air | 1.7 | 16.6 | 174 |
| 15.2 | 90 | 0.17 | 10.5 | Air | (2.5) | (11.3) | (119) |
| 7.6 | 91.5 | 0.08 | 10.5 | Air | >4.2 | 6.8 | <71 |
| 1.5 | 91.5 | 0.01 | 10.5 | Air | 13.0 | 2.2 | 23 |

t: wall thickness
d: outside diameter
T: time to complete circular cut
W = P.T.: energy required for complete cut

NOTES: 1. Data obtained on 155mm projectiles, M125 bomb, M55 rocket

2. Numbers in parentheses could be achieved with improved or additional gas jets

TABLE 2. Cutting of Aluminum Cylinders by Gas-Assisted $CO_2$ Laser

| t mm | d mm | t/d - | P kW | Gas - | Speed cm/s | T sec | W kWs |
|---|---|---|---|---|---|---|---|
| 9.4 | 88 | 0.11 | 3.0 | $CO_2$ | >0.84 | <32.9 | <99 |
| 9.4 | 88 | 0.11 | 10.5 | Air | 4.2 | 6.5 | 68 |
| 6.3 | 88 | 0.07 | 10.5 | Air | 8.5 | 3.2 | 34 |

t: wall thickness
d: outside diameter
T: time to complete circular cut
W = P.T: energy required for complete cut

NOTES: 1. Data obtained on M55 warhead

2. Survival of the burster tube was not demonstrated with P = 10.5 kW

TABLE 3. Cutting of Composite Cylinders by Gas-Assisted $CO_2$ Laser

| $t_1$ mm | $t_2$ mm | $t_3$ mm | P kW | Gas - | Speed cm/s | T sec | W kWs |
|---|---|---|---|---|---|---|---|
| 5.1 | 0 | 0 | 3.0 | $CO_2$ | 3.50 | 7.9 | 24 |
| 5.1 | 2.5 | 7.6 | 3.0 | $O_2$ | 2.54 | 10.9 | 33 |
| 5.1 | 2.5 | 8.9 | 6.0 | $CO_2$ | 0.64 | 43.2 | 259 |
| 5.1 | 2.5 | 10.7 | 6.0 | $CO_2$ | 0.42 | 65.8 | 295 |
| 5.1 | 2.5 | 0 | 6.0 | $CO_2$ | 1.27 | 21.8 | 131 |
| 5.1 | 2.5 | 0 | 3.0 | $O_2$ | 2.54 | 10.9 | 33 |
| 5.1 | 0 | 0 | 10.5 | Air | 17.0 | 1.6 | 16.8 |
| 5.1 | 2.5 | 9.7 | 10.5 | He | 2.54 | 10.9 | 114 |

$t_1$: wall thickness of outer cylinder (Fiberglass tube)

$t_2$: motor case (steel)

$t_3$: warhead (aluminum, innermost cylinder)

$d_1$ = 124.5mm

$d_2$ = 115mm, airspace between outer cylinder and rocket assembly

$(t_1 + t_2 + t_3)/d_1 = 0.04 - 0.20$

t: time required to complete circular cut

W = P.T: energy required for complete cut

NOTE: Data obtained on M55 rocket assembly

which we believe should result in separable parts provided the jet geometry is optimized. In our experiments, we did not obtain separation with those parameters. The results in Table 1 (Steel) suggest the following conclusions:

a. Over the range of 3-10 kW of laser power, with oxygen assist, the energy requirements are not a strong function of laser power.

b. An air jet requires about twice the laser energy for the same cut, compared to an oxygen assisted cut. However, cutting 15.2mm of steel (155mm projectiles) is not possible at 3 kW laser power with air jets.

c. The specific power requirement (in units of kW of laser power per mm wall thickness per cm/s cutting speed) for steel is 0.13-0.22 with oxygen assist, and 0.33-0.54 with air, increasing with laser power over the range investigated here (Table 4). Within this range, trade-offs between laser power and cutting speed are possible.

d. The maximum usable laser power is between 10 to 15 kW. We observed incipient problems adversely affecting cutting performance at powers above 9 kW.

e. With 15.2mm wall thickness we experienced separation problems, especially with the air jet and the highest laser power. No problems were noted for thicknesses below 10mm.

The cutting data of Aluminum cylinders are shown in Table 2. No separation problems were noted, but with 10.5 kW laser power we could not prevent excessive laser powers behind the cut (burster tube was cut also). The specific power requirement is between 0.2 to 0.26 with air, and 0.38 with $CO_2$ (Table 4). The cut with $CO_2$ is cleaner and narrower than the corresponding cut with an air jet.

The composite (concentric) cylinder data are summarized in Table 3. Again, $CO_2$ jets produced the cleanest cuts with the least material removed, but the energy requirements were much higher than with air or oxygen (Table 4). The irregular air space between the outer fiberglass tube and the rocket assembly proper did not affect the cutting speed in any significant manner.

## 5. CONCLUSIONS

Using full scale, realistically simulated chemical ordnance materiel, and industrially rated CW $CO_2$ lasers of 3.0, 6.0 and 10.5 kW delivered power, we demonstrated in principle the feasibility of using such lasers in the Demilitarization Process. All cuts of interest require less than

TABLE 4. Specific Power Requirements for Gas-Assisted Laser Cutting

| Material | Thickness | Gas | Laser Power | | |
|---|---|---|---|---|---|
| - | mm | - | 3 kW | 6 kW | 10.5 kW |
| Steel | 15.2 | $O_2$ | 0.13 | 0.19 | 0.22 (0.16) |
| Steel | 15.2 | Air | No | - | 0.41 (0.28) |
| Steel | 7.6 | Air | - | - | 0.33 |
| Steel | 1.5 | Air | - | - | 0.54 |
| Aluminum | 9.4 | $CO_2$ | 0.38 | - | - |
| Aluminum | 9.4 | Air | - | - | 0.26 |
| Aluminum | 6.3 | Air | - | - | 0.20 |
| Fiberglass | 5.1 | Air | - | - | 0.12 |
| Fiberglass | 5.1 | $CO_2$ | 0.17 | - | - |
| Composite | 16.5/18.3 | $CO_2$ | - | 0.57/0.78 | - |
| Composite | 17.3 | He | - | - | 0.24 |
| Composite | 15.2 | $O_2$ | 0.08 | - | - |

NOTES: 1. Data from Tables 1-3

2. Power requirements listed in units of kW per mm thickness per cm/s cutting speed

100 kWs of laser energy. Assuming 10% overall electrical efficiency and a unit cost of 2 cents per kilowatt-hour, the electrical operating cost per cut is less than 1/2 cent. The cuts of interest can be completed in less than 20 sec. With multiple work stations for one laser system the dead time between the cuts (as dictated by the required handling, moving and repositioning of the work pieces) can be reduced to the time required to switch the laser beam from one work station to another one, which is negligible. With the above assumptions, one laser unit can make more than 180 cuts per hour. The potential production rates are high and the operating cost moderate. The required laser power is at least 3 kW if oxygen jets can be used, and at least 6 kW (estimated) if only air jets and similar less reactive gases can be tolerated. Powers higher than 12 kW (estimated) cannot be efficiently used in all anticipated applications.

We investigated only gas-jet assisted cutting. It is possible that in some applications gas jets can not be tolerated because of possible dispersion of agent, for example. It appears feasible that pulsed lasers, or CW lasers with super-imposed pulses could be used instead[7,11] for such critical applications.

The problems of transporting the laser beam to the work piece (inside a contaminated environment) need to be investigated: Reliable, blast proof windows are required between the clean and the contaminated areas, and the required optical focusing elements inside the work area must maintain their optical quality for sufficiently long periods.

The question regarding the "best" laser system for cutting chemical munitions on a production line cannot be readily answered. Industrially rated laser systems are available today (Oct 76) for about $40-50 per watt delivered output. The results presented earlier show that smaller lasers perform the same cutting operations more efficiently (Tables 1-4), that is with less laser energy required for the same finished product. This advantage is compensated for by the generally higher overall efficiency of larger systems. The experiments reported here, on geometries appropriate for demil work indicate also that the higher powers cannot be as effectively controlled as required in some applications peculiar to chemical munitions.

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[11] J. E. Robin and P. Nordin, "Improved CW Laser Penetration of Solids Using a Superimposed Pulsed Laser," Applied Physics Letters, Vol. 29, No. 1 (1 Jul 76), pp. 3-5.

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